# The Mg–$\sigma$ Relation of Elliptical Galaxies at Various Redshifts

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**Abstract.** The correlation between the Mg absorption index and the velocity dispersion ($\sigma$) of local elliptical galaxies is very tight. Because the Mg absorption depends on both metallicity and age of the underlying stellar population the observed Mg–$\sigma$ relation constrains the possible variation in metallicity and age for a given velocity dispersion. For a time interval with no change in metallicity any variation of the Mg index is caused only by the aging of the stars.

We have measured the Mg absorption and velocity dispersion of ellipticals in three clusters at a redshift of $z = 0.37$ and established their Mg–$\sigma$ relation. For any given $\sigma$, the measured Mg absorption is weaker than the mean value for local ellipticals. Since the evolution of bright cluster ellipticals between $z = 0.4$ and today is most probably only 'passive' this reduction in Mg can be attributed solely to the younger age of the stellar population. The small weakening of the Mg absorption of the distant galaxies compared to the local values implies that most of the stars in cluster ellipticals must have formed at high redshifts ($z_f > 2 \ldots 4$).

The Mg–$\sigma$ test is a very robust method to investigate the evolution of elliptical galaxies and has several advantages over traditional methods using luminosities. A remaining problem is the aperture correction necessary to calibrate observations of galaxies at different distances. Here, we show that our general conclusions about the epoch of formation still hold when aperture corrections are calculated assuming a dependence of the radial gradient of $\sigma$ on the galaxy's effective radius rather than assuming no dependence as was done in all previous studies.

## 1 The Local Mg–$\sigma$ Relation

It is well known that all dynamically hot galaxies in the local universe follow the same linear relationship between the Mg absorption around $\lambda_0 \approx 5170$ Å and the internal velocity dispersion $\sigma$ (Dressler et al. 1987, Bender et al. 1993). Although the galaxies span a wide range in Mg and $\sigma$, the Mg–$\sigma$ relation is very tight. A sample of luminous Coma ellipticals ($\lg\sigma \geq 2.3$), e. g., with $\mathrm{Mg}_2 \in [0.25, 0.36]$ mag has a standard deviation from the linear fit of only $\sigma_{\mathrm{int}} = 0.011$ mag. $\mathrm{Mg}_2$ as defined in the Lick system (Faber et al. 1985) comprises mainly the molecular absorption of MgH. Because the measurement of this index in redshifted galaxies is very noisy we use the atomic $\mathrm{Mg}_b$ index instead. A linear transformation from $\mathrm{Mg}_2$ to $\mathrm{Mg}_b$ enables us to still use the 7 Samurai sample of Coma and Virgo ellipticals as the comparison at zero redshift. Both from observational (Gonzalez 1993) and theoretical data (stellar population synthesis of Worthey 1994) we derived consistently: $\mathrm{Mg}_b/\text{Å} = 14.9 \pm 0.5 \cdot \mathrm{Mg}_2/\mathrm{mag}$. In

figure 1 small circles present the $\mathrm{Mg}_b$–$\sigma$ relation of the local comparison sample. A principal component analysis yields as best fit:

$$\mathrm{Mg}_b = 2.7 \lg \sigma_0 - 1.65 \tag{1}$$

The dependence of $\mathrm{Mg}_b$ on age and metallicity can be explored using stellar population synthesis models. From Worthey's 1994 models we derived the following formula that holds for ages $t > 3$ Gyrs and metallicities $-2 < \lg Z/Z_\odot < +0.25$:

$$\lg \mathrm{Mg}_b = 0.20 \lg t + 0.31 \lg Z/Z_\odot + 0.37 \tag{2}$$

This formula allows to determine the maximum variation of both relative age and relative metallicity as it is constrained by the very tightness of the $\mathrm{Mg}_b$–$\sigma$ relation. For a given velocity dispersion $\sigma$ (with $\lg \sigma \geq 2.3$) and zero variation in metallicity or age, resp., we find:

$$\Delta t/t < 0.17 \quad \text{and} \quad \Delta Z/Z < 0.11 \tag{3}$$

This narrow constraint on the age spread of cluster ellipticals implies that they did not form continuously at the same rate but that there was a rather short formation epoch of these galaxies. If, e.g., the majority of ellipticals were formed 12 Gyrs ago, then the scatter in age would be about 2 Gyrs. However the formation epoch itself can only be determined by comparing the relative ages of galaxies at zero and a significantly higher redshift.

## 2 The $\mathrm{Mg}_b$–$\sigma$ Relation at Redshift $z = 0.37$

As a first step we have established the $\mathrm{Mg}_b$–$\sigma$ relation of elliptical galaxies in three clusters at a redshift of $z = 0.37$ (*Abell 370, CL 0949+44* and *MS 1512+36*) (Bender et al. 1996). The spectra were taken with the 3.5m telescope at the Calar Alto observatory and the 3.6m and the NTT at ESO with total integration times per galaxy on the order of 8 hours. Very careful data reduction had been applied because in the relevant wavelength range ($\lambda(\mathrm{Mg}_b, z = 0.37) \approx 7080$ Å) the spectra are heavily contaminated by strong night sky emission lines and telluric absorption bands (Ziegler and Bender 1997).

Figure 1 presents the datapoints for the distant galaxies together with the local $\mathrm{Mg}_b$–$\sigma$ relation. The first thing to note is that all distant ellipticals have lower $\mathrm{Mg}_b$ line strengths than the local mean value at the same velocity dispersion. This is clear evidence for evolution of the stellar populations of elliptical galaxies between $z = 0.37$ and now. On the other hand the reduction in $\mathrm{Mg}_b$ is very weak, on average $<\Delta \mathrm{Mg}_b> = -0.37 \pm 0.08$ Å. This can be reconciled with current stellar population models only if there was virtually no new star formation in today's cluster ellipticals since $z = 0.37$ but only 'passive' evolution of the aging stars. Therefore, the metallicity did most probably not change at all and the reduction in $\mathrm{Mg}_b$ can be fully attributed to the younger age of the distant galaxies. Setting $\Delta Z = 0$, equation 2 together with equation 1 can be

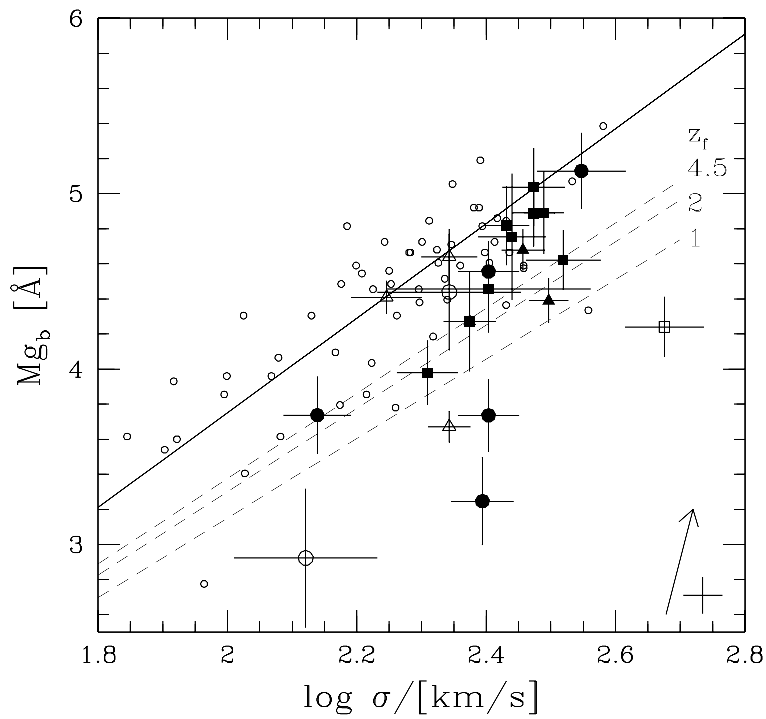


**Fig. 1.** $\mathrm{Mg}_b - \sigma$ pairs at $z = 0.37$ (big symbols with errorbars) compared to the local $\mathrm{Mg}_b$–$\sigma$ relation (small circles: Coma and Virgo elipticals, typical errorbar in lower right corner). Arrow: aperture correction applied. Dashed lines: expected $\mathrm{Mg}_b$–$\sigma$ relations at $z = 0.37$ for $z_f = 1, 2, 4.5$ and $H_0 = 50, q_0 = 0.5$.

transformed to deduce theoretical curves of the $\mathrm{Mg}_b$–$\sigma$ relation at the observed redshift $z = 0.37$:

$$\frac{\mathrm{Mg}_b\,(z=0)}{\mathrm{Mg}_b\,(z)} = \left(\frac{\mathrm{age}\,(z=0)}{\mathrm{age}\,(z)}\right)^{0.20} \tag{4}$$

The age of an object depends mainly on its redshift of formation $z_f$ and less on the cosmology $(H_0, q_0, \Lambda)$. In figure 1, the dashed lines correspond to the expected $\mathrm{Mg}_b$–$\sigma$ relation at $z = 0.37$, if $z_f$ were 1, 2 or 4.5, resp.. The small weakening of $\mathrm{Mg}_b$ to a look–back time of $\approx 5$ Gyrs constrains the age of the stellar populations so that the majority of the stars in elliptical cluster galaxies were formed at high redshifts $z_f \geq 2$. For the most luminous ellipticals, where the reduction in $\mathrm{Mg}_b$ is even lower, $z_f$ could be as high as 4. This imposes great problems on current theories on the structure formation using Cold Dark Matter models, because contrary to these models smaller objects seem to be younger than big ones and formed at later times. But a large dynamically relaxed stellar system most probably did not form within only 1 Gyr after the Big Bang as is

fixed by $z_f = 4$ in all reasonable cosmologies. A way out of this paradigm is a model in which the stars indeed existed already at $z \geq 4$ in a common gravitational potential but the galaxies were formed only at much later times through the collapse of these dark matter halos and/or through the dissipationless merging of smaller halos. The smaller elliptical galaxies could either have a much more extended formation epoch or experience events during their evolution which add new populations of stars and therefore lower their mean age.

The evolution of the stellar population as measured by the $\mathrm{Mg}_b$–$\sigma$ test can be transformed into a change in luminosity with the help of population synthesis models. From the Worthey and Bruzual & Charlot (1997) models we found consistently the following linear relation between the reduction in $\mathrm{Mg}_b$ and the increase in the $B$–band luminosity valid for ages greater than 1.5 Gyrs and metallicities between half and twice solar:

$$\Delta\mathrm{M}_B\,[\mathrm{mag}] \quad\approx\quad 1.35 \pm 0.1\,\Delta\mathrm{Mg}_b\,[\mathrm{\AA}] \tag{5}$$

Thus, the distant cluster ellipticals are on average brighter in the $B$–band by $<\Delta\mathrm{M}_B>= -0.50 \pm 0.11[\mathrm{mag}]$ than local ones. This is quantitatively consistent with the brightening obtained via the Faber–Jackson relation.

The $\mathrm{Mg}_b$–$\sigma$ test is, therefore, a powerful and reliable tool to investigate the evolution of elliptical galaxies. Over all other methods using luminosities or colors it has the advantage to be free of problems like foreground and internal extinction and K–corrections. It also depends only very weak on the initial mass function. The accurate determination of the luminosity evolution by this method, therefore, makes it possible for the first time to calibrate elliptical cluster galaxies as standard candles. Together with the fundamental plane relations the cosmological parameter $q_0$ can be significantly constrained (see the contribution by Bender et al., this conference or 1997).

The weak part of the $\mathrm{Mg}_b$–$\sigma$ test is the aperture correction necessary to calibrate observations of galaxies at different distances. Even if our aperture size were the same as was used for the observations of the local comparison sample we would average our measured values over a much greater fraction of the galaxies. Indeed, the 7 Samurai determined central values whereas we integrate out to more than the effective radius ($r_e$). Because both $\mathrm{Mg}_b$ and $\sigma$ have radial gradients an aperture correction has to be applied. From spectroscopic observations of ellipticals with sufficient $S/N$ out to several $r_e$ (Saglia *et al.*, unpublished) we found the following gradients:

$$\mathrm{Mg}_b = -0.87\,\lg(r/r_e) + c \tag{6}$$

$$\lg\sigma(r) = -0.11\,(r/r_e)^{3/4} + c \tag{7}$$

The gradient of $\lg\sigma$ depends on the effective radius in a non logarithmic manner unlike those used in previous studies but which were determined from data with a much lower radial extent (e.g. Jørgensen et al. 1994) and falls off steeply at $r_e$. Because we could not determine the effective radii of all the observed distant ellipticals from our ground–based photometry (Ziegler 1997) we chose a representative value and applied the same aperture correction for all galaxies

in figure 1. Recently, we have been able to accurately measure $r_e$ for 9 galaxies from our HST images of *Abell 370* and *MS 1512+36* and, thus, apply individual aperture corrections. Figure 2 presents the same diagram as figure 1 but with $\mathrm{Mg}_b$ and $\sigma$ extrapolated to integrated mean values within $r_e$. Although individual galaxies changed their position in the new diagram our general conclusions about the age ($z_f$) and evolution are still valid with an average reduction in $\mathrm{Mg}_b$ of $<\Delta\mathrm{Mg}_b>= -0.34 \pm 0.19$ Å.

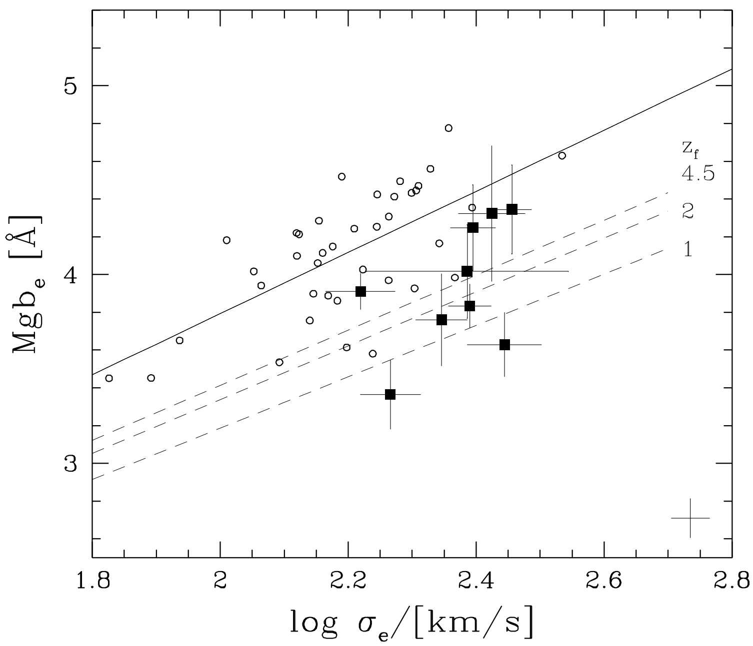


**Fig. 2.** Same diagram as figure 1 but with $\mathrm{Mg}_b$ and $\sigma$ extrapolated to integrated mean values within $r_e$.

## 3 The $\mathrm{Mg}_b$–$\sigma$ Relation at Higher Redshifts

Going to higher redshifts we expect to find a more prominent evolution in $\mathrm{Mg}_b$ because the stellar population gets still younger and the formation epoch is approached. The higher amount of evolution and the wider range in look–back time should enable us to reduce further the errors in the calibration of elliptical cluster galaxies as standard candles and allow us to even better constrain the value of the cosmological parameter $q_0$. But if future data at high redshifts would show evolution allowing merging/accretion events in addition to passive

evolution, then possible variations on the velocity dispersions must be taken into account.

Clearly, the spectroscopy of very faint objects will be a major challenge. Observing at higher redshifts means that the $\mathrm{Mg}_b$ absorption line moves more and more into the red wavelength range with a strongly increasing sky contamination. The next favourable redshift bins where there is a slight depression in the sky emission are: $0.575 < z < 0.583$ and $0.754 < z < 0.780$. The decrease in brightness of the galaxies due to their greater distance (1. . . 2 mags) might just be compensated by their evolutionary brightening. In order to get spectra with $S/N$ as good as we have obtained at $z = 0.37$ the suggested observations can only be done with a big enough telescope like the VLT together with a spectrograph of superb efficiency like FORS. Exposure times would be on the order of 1.5. . . 2 hours. Multi–object spectroscopy will be the appropriate method if the apertures are large enough to collect a sufficiently large area of the sky around each object in order to be able to cope with the sky subtraction.

## 4 Conclusions

Determining the $\mathrm{Mg}_b$–$\sigma$ relations at various redshifts is a powerful and robust method to measure the evolution of elliptical galaxies. From the first application at a redshift of $z = 0.37$ we could already make two firm conclusions: first, the stellar population of elliptical cluster galaxies evolves predominantly passive between this redshift and today and second, the epoch of formation of the stars that mainly make up the ellipticals today is at high redshifts. The evolution in $\mathrm{Mg}_b$ can be reliably transformed into an increase of the $B$–magnitude, thus, allowing the calibration of elliptical cluster galaxies as standard candles.

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